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Neutron-induced light-ion production from Fe, Pb and U at 96 MeV

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Double-differential cross sections for light-ion production (up to A=4) induced by 96 MeV neutrons have been measured for ^{nat}Fe, ^{nat}Pb and ^{nat}U. The experiments have been performed at the The Svedberg Laboratory in Uppsala, using two independent devices, MEDLEY and SCANDAL. The recorded data cover a wide angular range (20º - 160º) with low energy thresholds. The work was performed within the HINDAS collaboration studying three of the most important nuclei for incineration of nuclear waste with accelerator-driven systems (ADS). The obtained cross section data are of particular interest for the understanding of the so-called pre-equilibrium stage in a nuclear reaction and are compared with model calculations performed with the GNASH, TALYS and PREEQ codes.

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1. Introduction

To achieve a better understanding of nucleon-induced reactions in the 20-200 MeV range and develop improved models, detailed information on light-ion production in these reactions is needed. The need for such data comes also from a large amount of applications. Incineration of nuclear waste using accelerator-driven systems (ADS) is one example [1]. For this reason, the interest in nucleon-induced reactions has been growing in the last few years. This interest has been manifested in part by extensive experimental campaigns, like the one carried out by several laboratories in Europe within the framework of HINDAS [2]. The results presented here are part of this program and concern double-differential cross sections for light-ion emission (up to A=4) induced by 96 MeV neutrons on ^{nat}Fe, ^{nat}Pb and ^{nat}U [3].

2. Experimental procedure

Experiments have been performed using the neutron beam available at the The Svedberg Laboratory (TSL) in Uppsala, Sweden. The neutron beam characteristics (neutrons are not mono-energetic, large beam spot at the target position, and, compared to proton beams relatively low intensity) lead us to use two independent detection systems in order to obtain satisfactory count rate, keeping at the same time systematical uncertainties within reasonable limits.

The MEDLEY setup [4] is made of eight Si-Si-CsI telescopes, allowing detection of light-ions up to A=4 with a low energy threshold. The statistics accumulated using the MEDLEY setup is relatively poor, due to the thin targets used and to the small solid angles covered by the telescopes. The angular resolution is dictated by the target active area and by the opening angle of the telescopes. It was calculated using Monte Carlo simulations of the experiment, and the typical values found are of the order of 5 degrees (FWHM).

In the case of the SCANDAL setup [5] the angular resolution is significantly improved by reconstructing proton trajectories using drift chambers. This device consists of two identical systems located on either side of the neutron beam. Each system uses two 2 mm thick plastic scintillators for triggering, two drift chambers for particle tracking and an array of 12 CsI detectors for energy determination. The emission angles of the particles are calculated using the trajectories in the drift chambers. The angular resolution achieved is of the order of 0.3 degrees. A multi-target system (MTGT) [6] is used to increase the count rate without impairing the energy resolution. The MTGT allows up to seven targets to be mounted simultaneously, inter-spaced with multi-wire proportional counters. In this way it is possible to study several reactions at the same time since we can determine from which target the particle has been emitted and apply corrections for energy losses in subsequent targets. In contrast to MEDLEY, SCANDAL has been used for proton detection only and with an energy threshold of about 35 MeV, however, with a much higher count rate and better angular resolution.

Due to the difficulties encountered when monitoring neutron beam intensities, the absolute cross section normalisation in neutron-induced reactions is a notorious problem. Therefore, the cross sections are measured relative to the H(n,p) cross section. For this reference cross section, the most recent measurements [7] claim an absolute uncertainty of 2 %. Values given in Ref. [7]

have been used to calculate the absolute cross sections presented in this work. Estimated systematic uncertainties affecting the experimental cross sections reported are below 5%.

3. Results

The light-ion spectra have been measured for ^{nat}Fe, ^{nat}Pb and ^{nat}U over the 20-160 degree angular range. The low-energy threshold was 4 MeV for hydrogen isotopes, 12 MeV for ^{3}He and 8 MeV for alpha particles registered with MEDLEY and 35 MeV for proton detection in SCANDAL. The measurements were done up to the maximum possible energy. The energy bin has been fixed to 4 MeV, governed by the energy resolution of the detectors and the accumulated statistics. Fig. 1a compares double-differential cross sections for proton production from iron at 20 degrees, independently measured by both detection systems. Similar results have been obtained for all measured (n,xp) reactions and over the full angular range. The found good agreement, in the energy range covered by both measurements, shows that systematical uncertainties related to cross-section normalisation are low. Fig. 1b shows the Fe(n,xp) cross-section measured with MEDLEY at 20 degrees together with data from Ref. [8], obtained using the magnetic spectrometer LISA. Also here, good agreement is found between the two measurements in the common energy range. Similar agreement has been found for the Pb(n,xp) reaction.

The experimental double-differential cross sections for the emission of hydrogen isotopes measured with MEDLEY are shown in Ref. [3]. Fig. 2 shows deduced energy-differential cross sections. The errors given in the figures are purely statistical.

Energy distributions are obtained from the double-differential cross sections using the Kalbach systematics [9] to extrapolate the experimentally available angular range over the entire range. Experimental information on the energy-differential cross sections is of great importance, since the agreement between calculations and experimental results for this observable is considered as a minimum condition to validate model predictions.

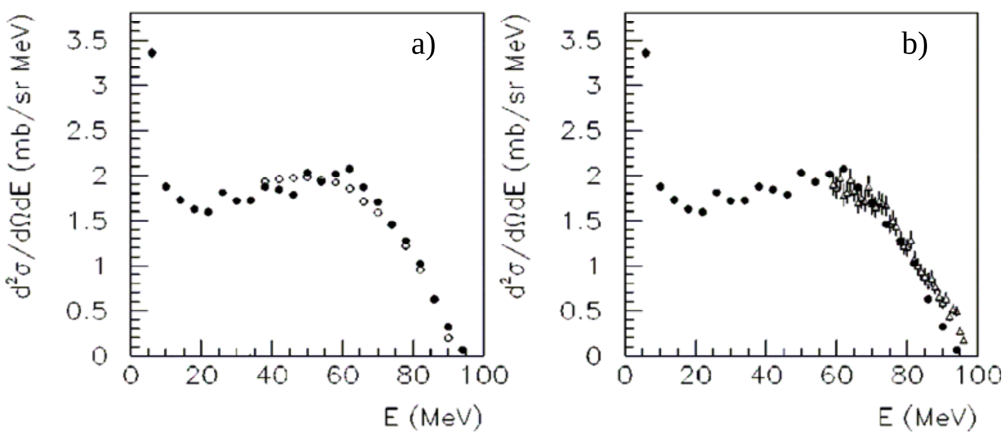

Figure 1. a) Double-differential cross sections for Fe(n,xp) at 20 degrees measured by MEDLEY (filled circles) and SCANDAL (open circles). b) Double-differential cross sections for Fe(n,xp) at 20 degrees measured by MEDLEY (filled circles) and data from Ref. [8] (open triangles).

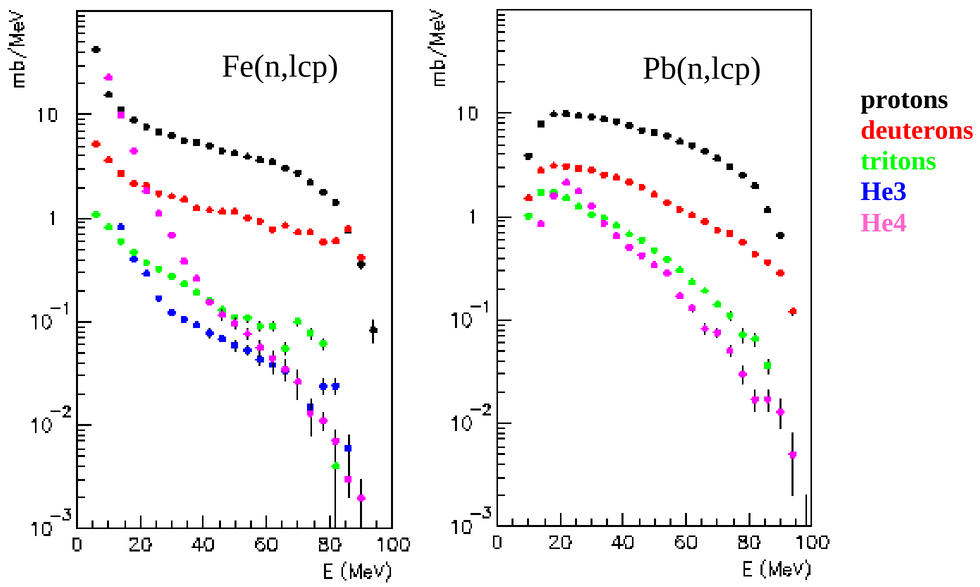

Figure 2: Energy-differential cross sections for the emission of light-ions induced by 96 MeV neutrons on ^{nat}Fe, ^{nat}Pb.

4. Comparison with theoretical calculations

In Fig. 3, the measured energy-differential cross sections for p, d, t and α for 96 MeV neutrons on lead are compared with model calculations. The GNASH code [10] describes the proton production rather well, while a strong underestimation is observed for the case of complex particles. Improvements have recently been done with the TALYS code [11], taking into account the contribution of direct pick-up and knock-out reactions in the complex-particle emission spectra. Even if the agreement in the production rates for complex particles is significantly better, there are still important differences in the shape of the distributions.

A completely different approach takes into account the complex-particle formation probability in the pre-equilibrium stage. This process is treated in the framework of a coalescence model. The code PREEQ [12] uses this approach to calculate energy distributions for particle emission at pre-equilibrium. The results show a good agreement with the data in both shape and amplitude of the distributions.

5. Summary

In this work experimental double-differential cross sections for light-ion production in 96 MeV neutron-induced reactions in iron, lead and uranium are reported. The extracted energy-differential cross sections have been compared with model calculations by the GNASH, TALYS and PREEQ codes. The comparison of these calculations with the experimental data shows clearly that, despite the better agreement obtained with the TALYS code compared to the old version of the exciton model used in the GNASH code, improvements are still needed for a deep understanding of the reaction mechanisms leading to emission of complex-particles. An alternative is given by the PREEQ code which takes the nucleon coalescence during the pre-equilibrium stage leading to cluster formation into account. This approach seems to give a better description of complex-particle emission in nucleon-induced reactions at intermediate energies.

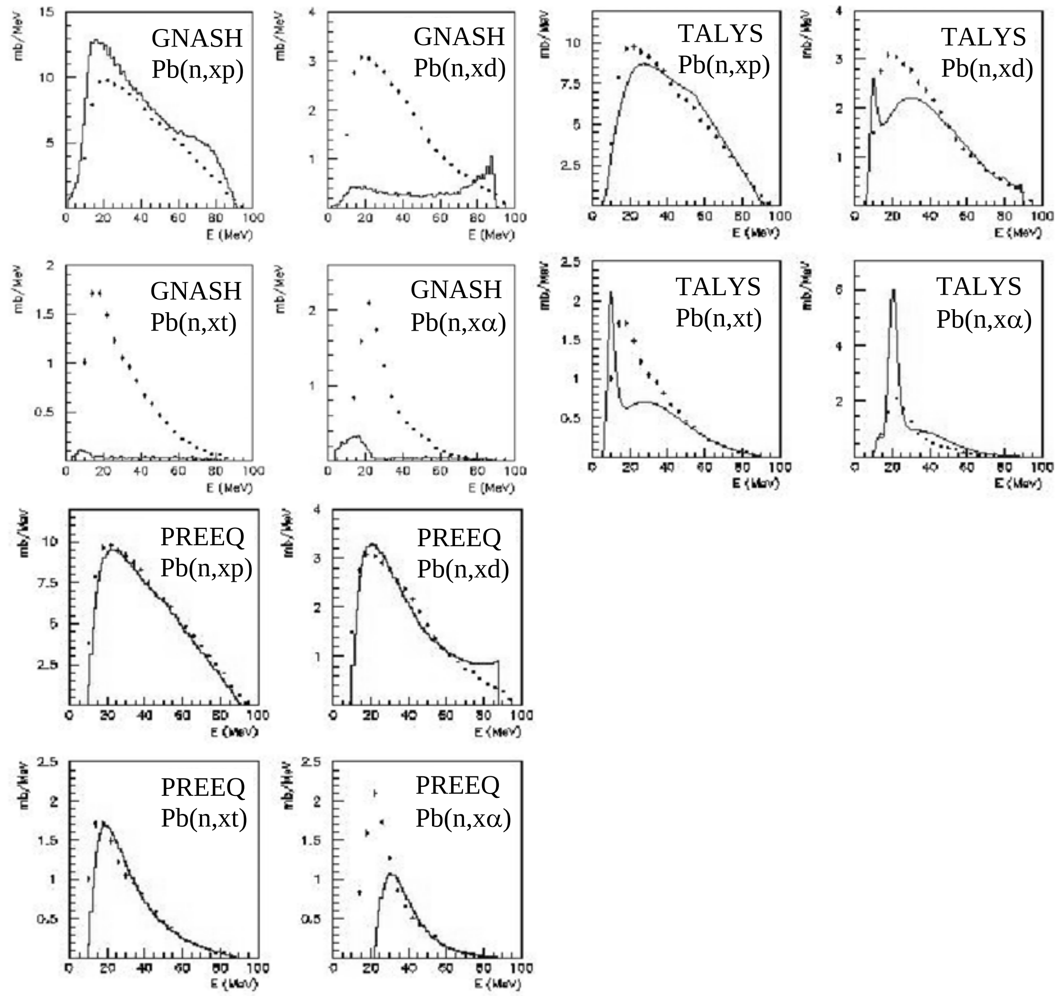

Figure 3: Energy-differential cross sections calculated using the GNASH, TALYS and PREEQ codes. The calculations have been done for 96 MeV neutrons on Pb and are shown as histograms. The experimentally obtained data are shown as points.

Acknowledgments

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